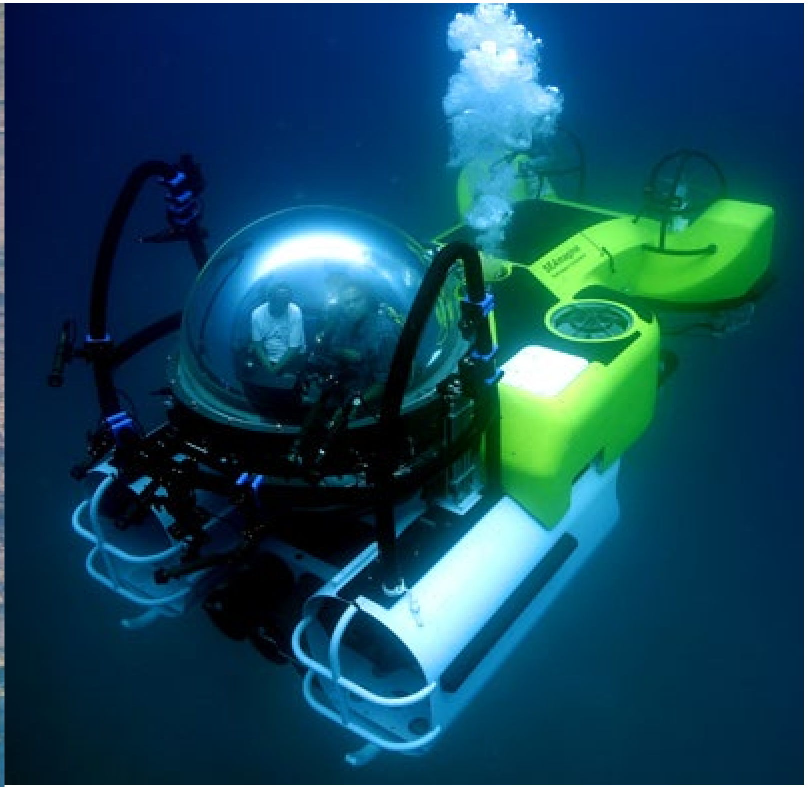
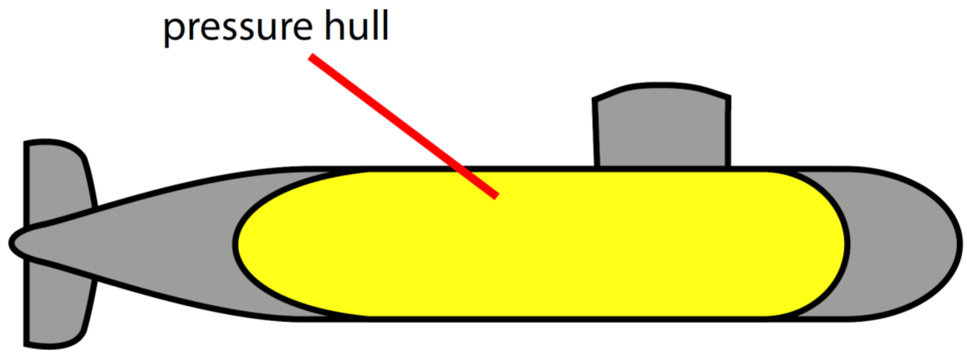
On Lightweight Design of Submarine Pressure Hulls

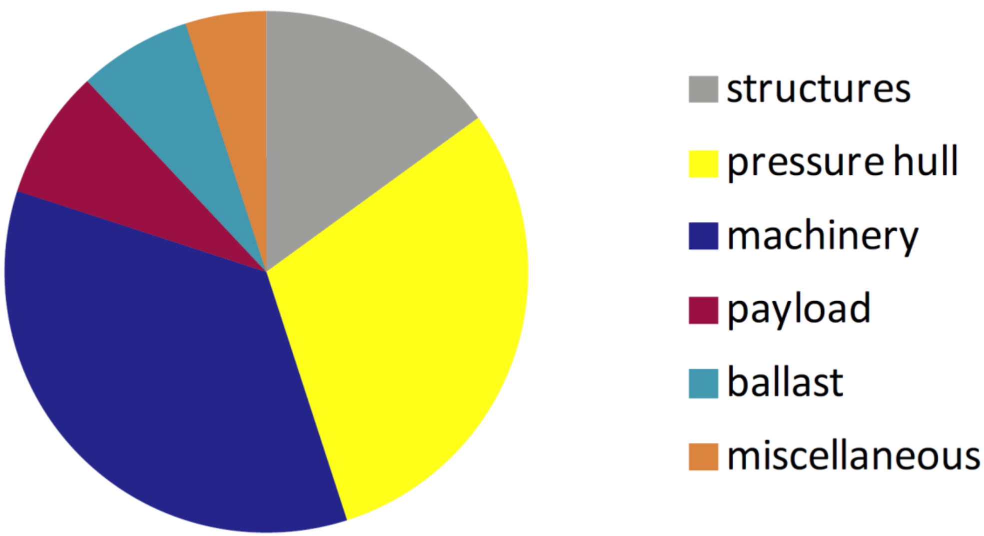
Introduction

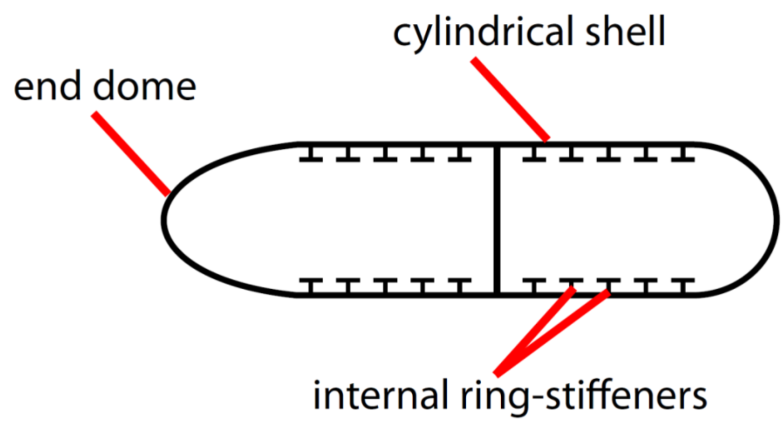


Introduction



submarine dry weight





Introduction

- Search for a lightweight solution

- Literature shows that
  - composite materials can be used for a lightweight pressure hull
  - description of composite mechanics and failure can be complex
  - only rough composite pressure hull models are optimized

Purpose of the present work

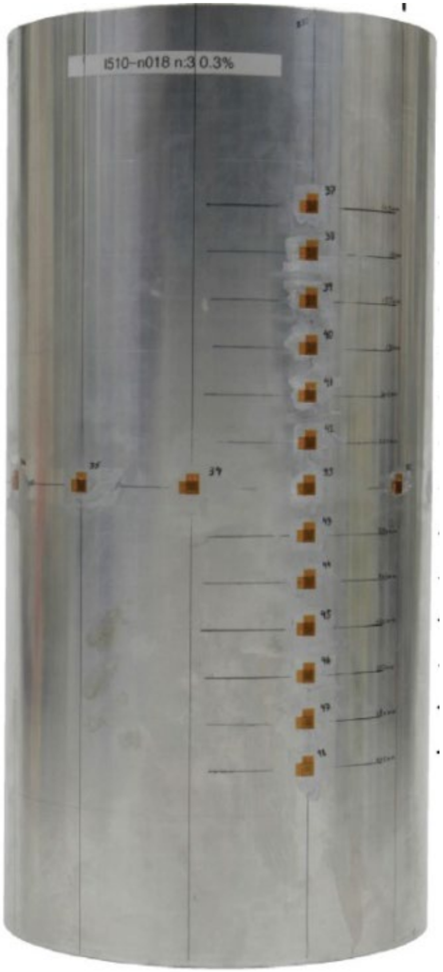
- Formulate a basis for a lightweight design framework that uses composite pressure hull FE models to accomplish an optimization procedure
- Indicate the weight savings found by this procedure

Content

- **Lightweight potential of conventional pressure hulls**
- Describe the composite pressure hulls
- Describe and perform the weight minimization
- Comparison
- Conclusions and recommendations

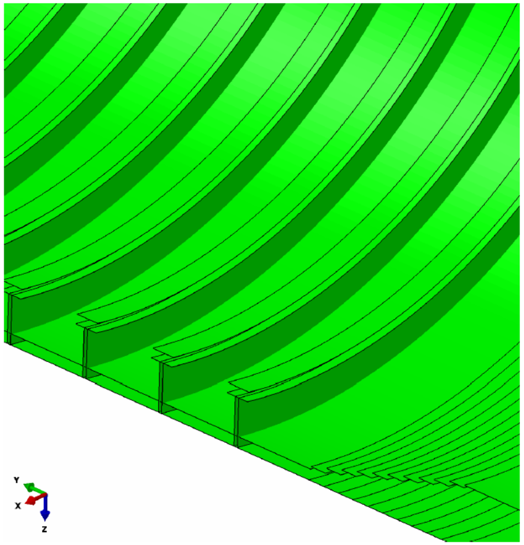
Reference pressure hull model

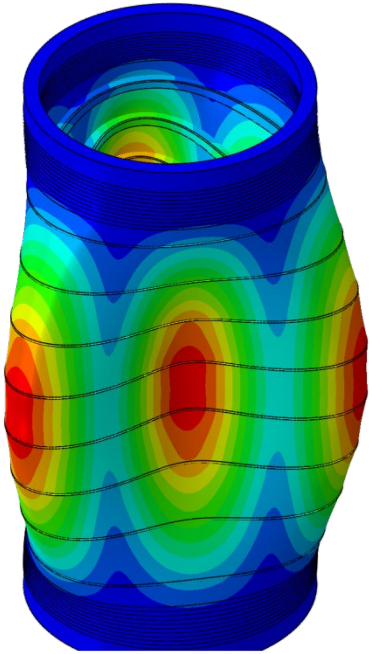
- The reference model is:
  - internally stiffened
  - geometry is measured
  - experimentally subjected to external pressure
  - measured with strain gauges
- Collapse at almost 8 MPa (= 80 bar)



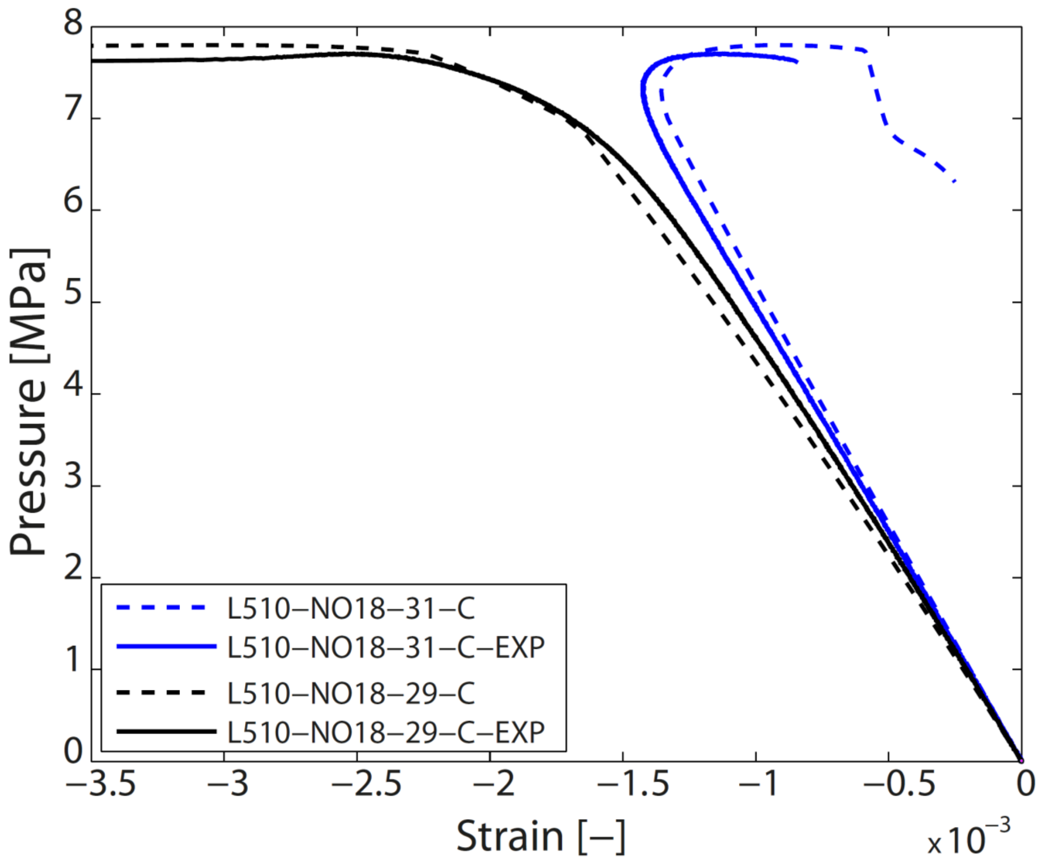
Reference FE model

- A FE model with shell elements is created
- Collapse is predicted with a non-linear buckling analysis with:
  - plasticity model for the material
  - modeled FE strain gauges

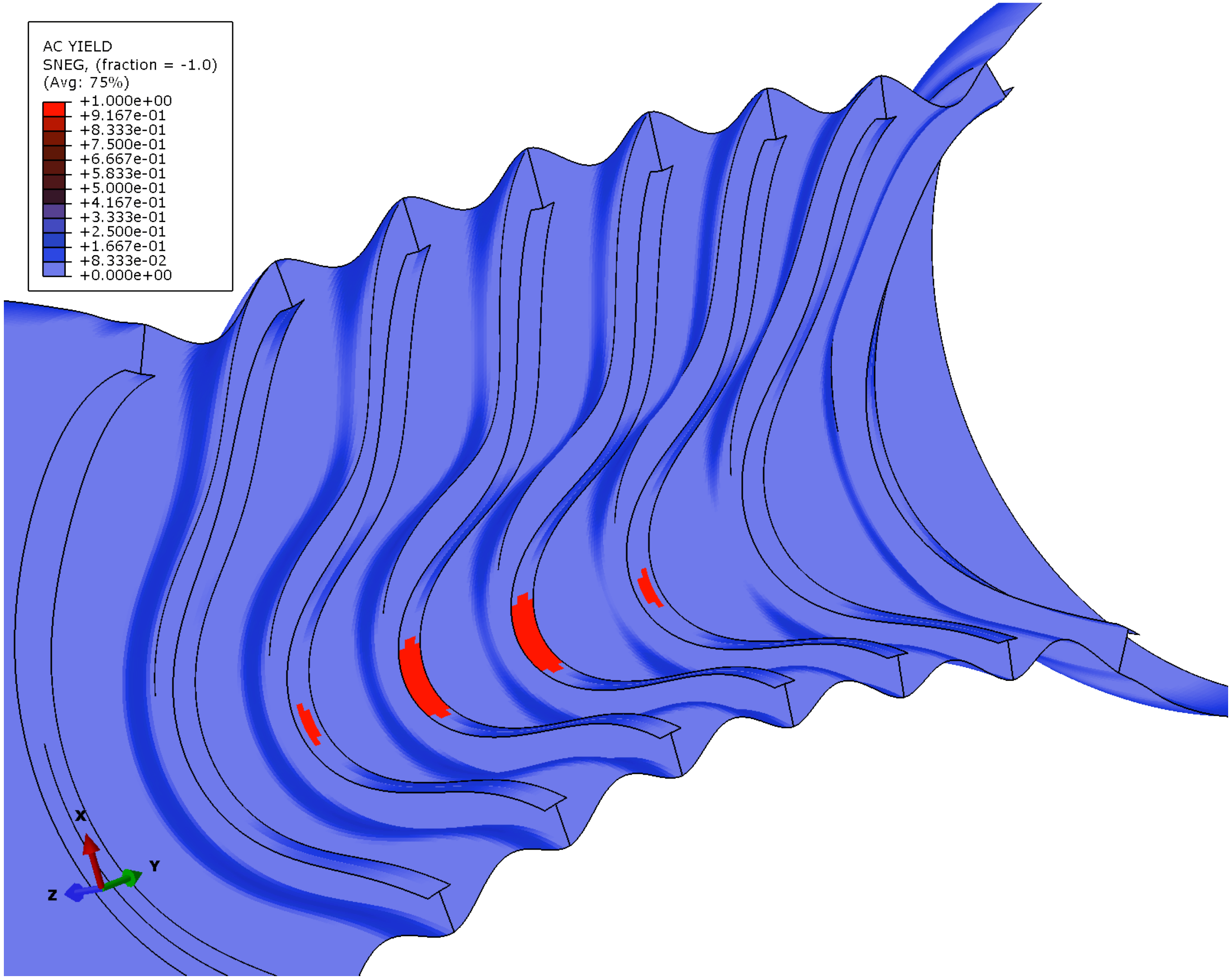




Reference FE model (cont.)

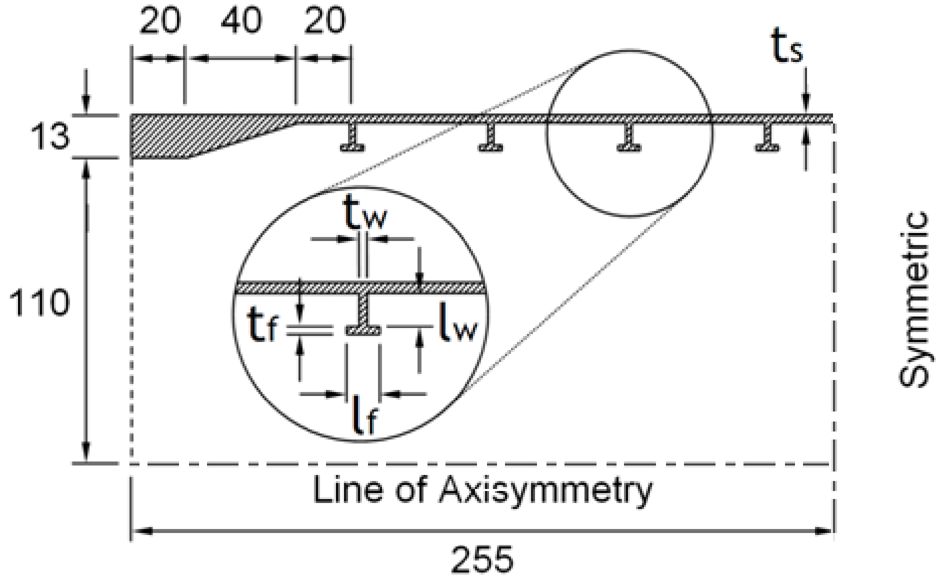


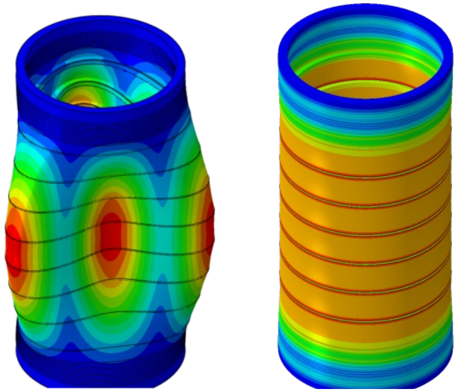
Reference FE model (cont.)



Reference: weight optimization

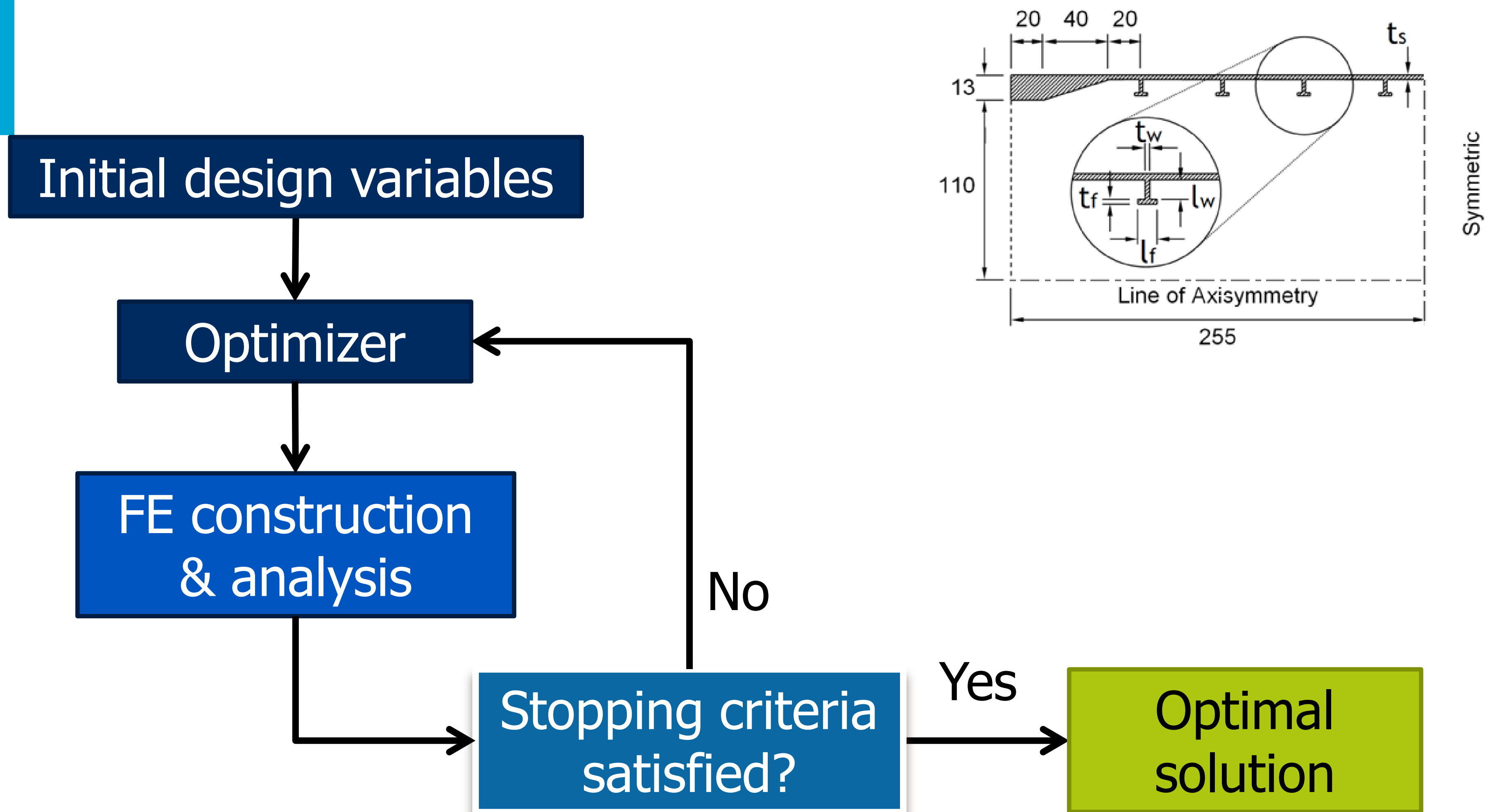
- Parametric FE description of reference model
  {stiffener dimensions, shell thickness & number of stiffeners}





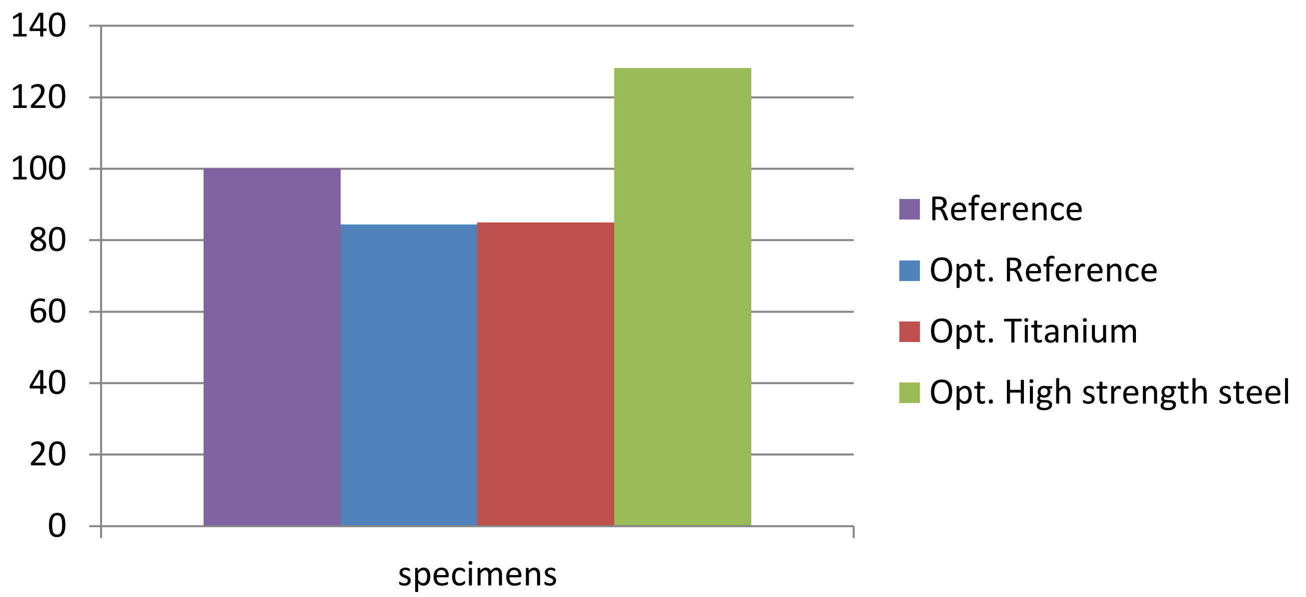
- Static load and linear buckling analysis are performed
- Unit weight minimization is performed

Reference: weight optimization



Results

- An reduction of 15% in weight is accomplished
- Construction in titanium showed similar results
- High strength steel (HY80) is 28% heavier than the reference



Content

- Lightweight potential of conventional pressure hulls
- **Describe the composite pressure hulls**
- Describe and perform the weight minimization
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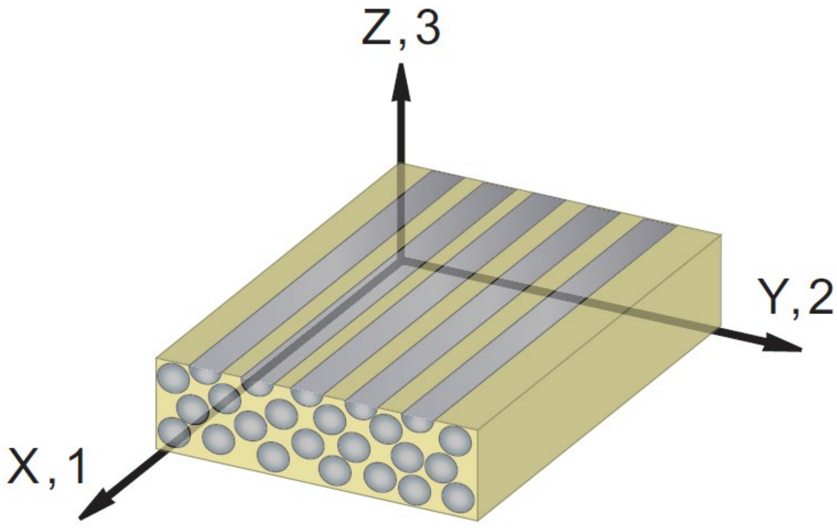
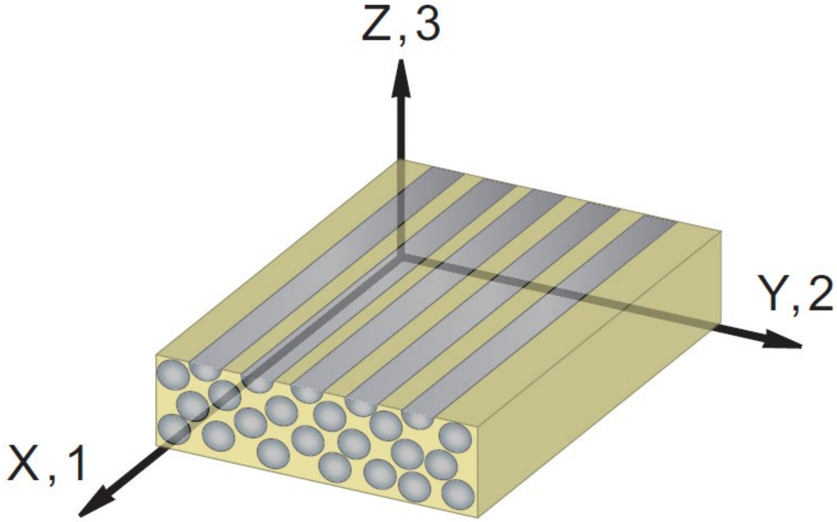
Composite & sandwich materials

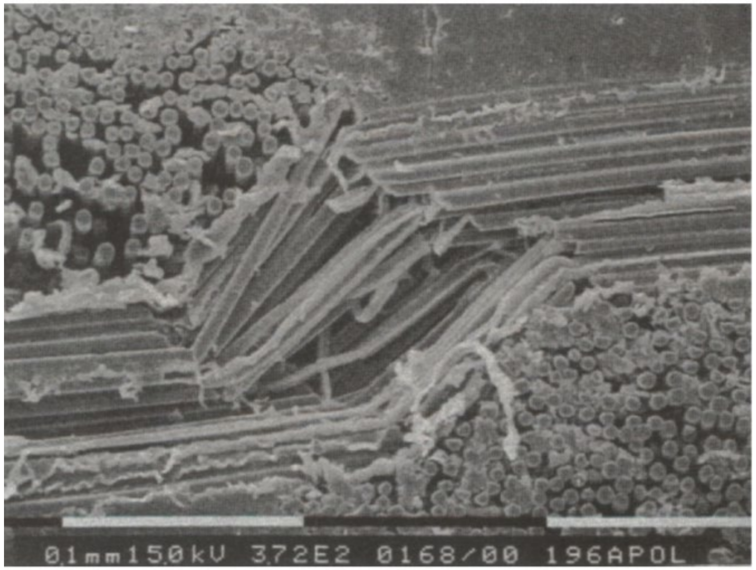
- Already widely applied in marine structures
- Focus is on fibrous composites and sandwiches
- Stacked composite plies form a laminate



Composite & sandwich materials

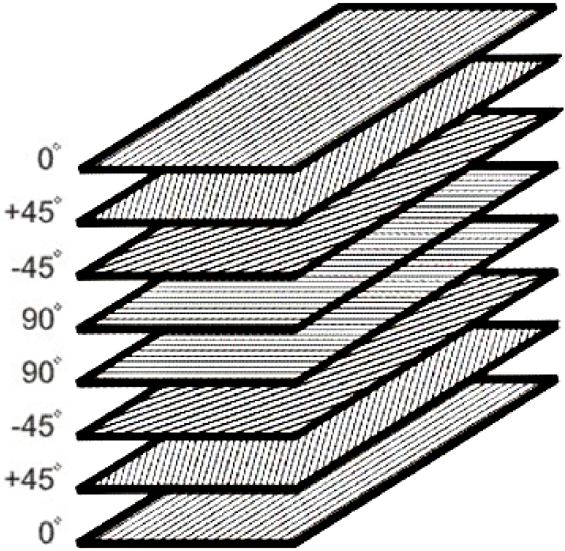
- Composites show direction dependancy
- Laminates can be tailored
- Mechanics and failure are more complex than metal

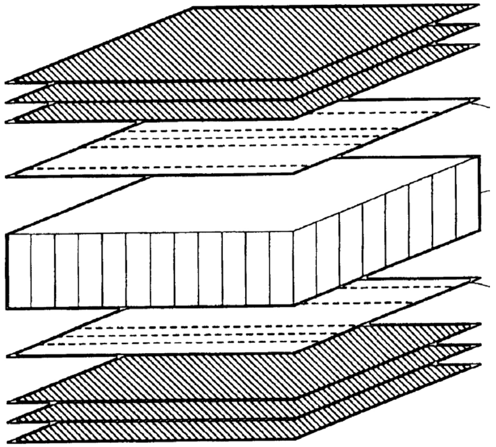


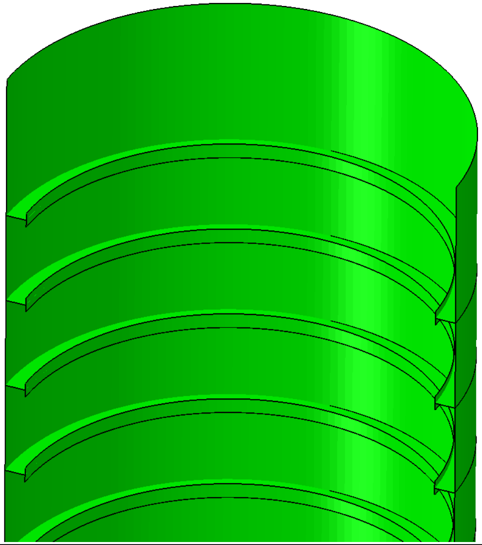


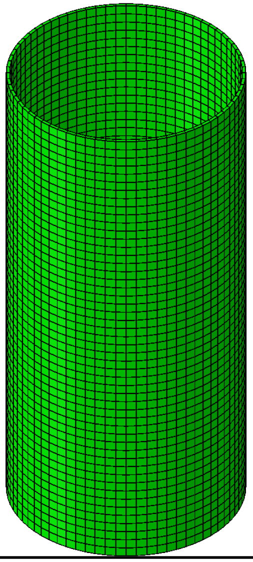
Lightweight design in FE

- Composite & sandwich are modeled in FE
- The FE model is comparable to the reference
- Collapse predictions are performed







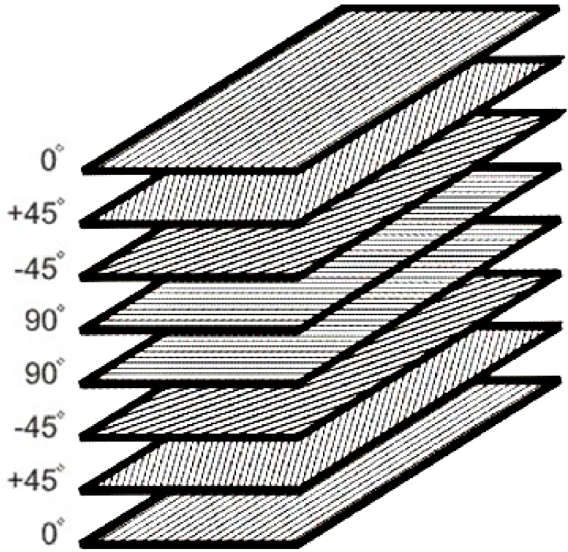


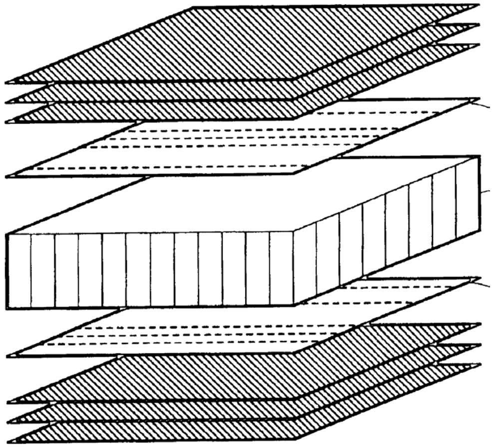
Lightweight design in FE

- Computational intensive for optimization

Example:
Calculation time is 6 minutes
16-ply symmetric laminate:

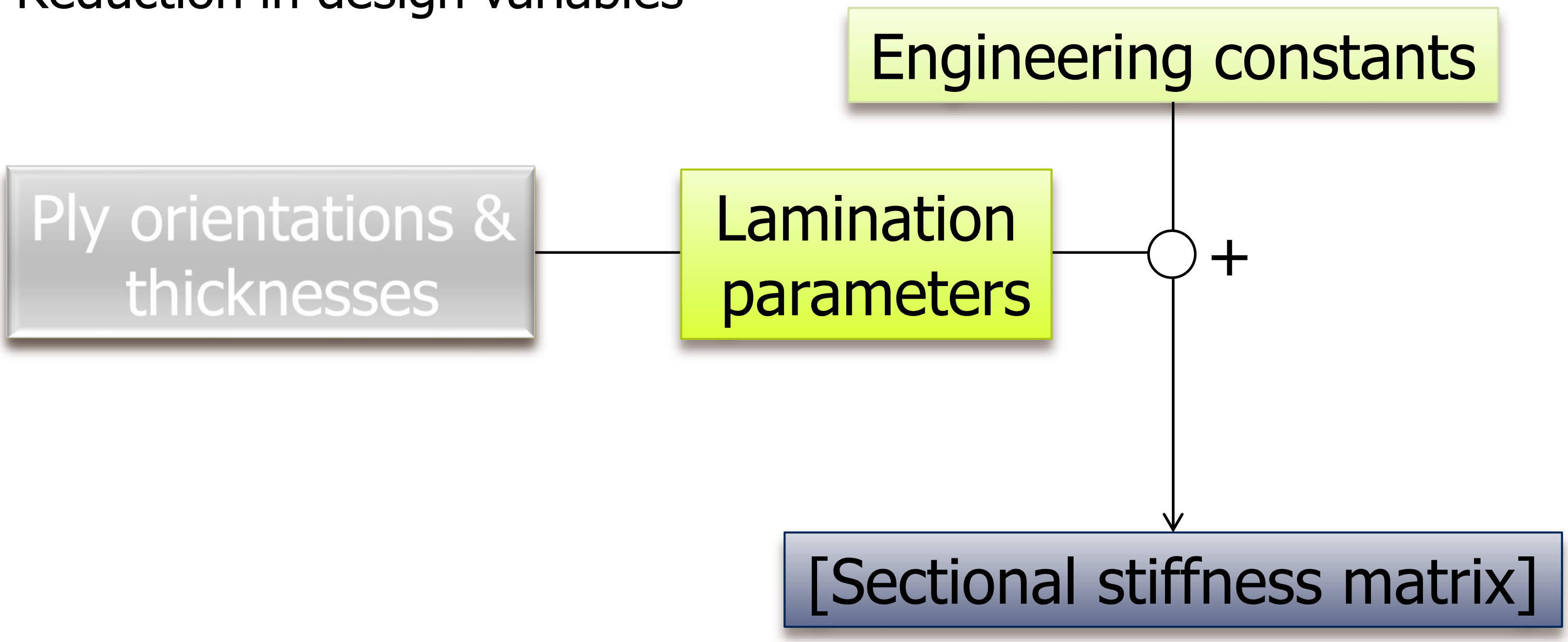
$4^8 * 6 = 393216$ minutes
= 39 weeks





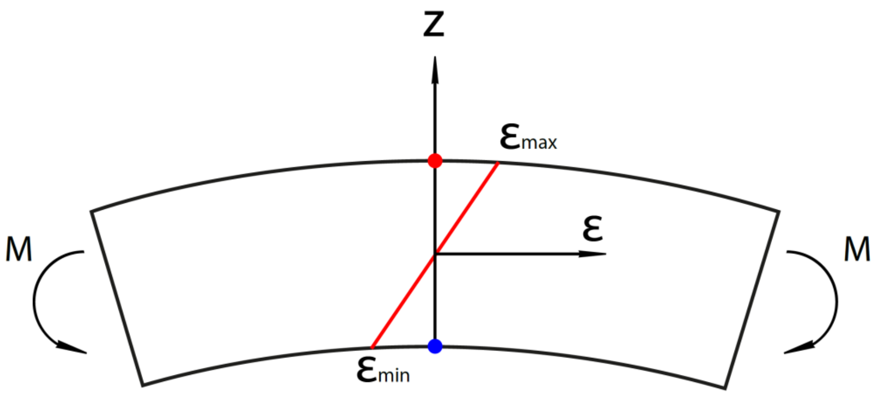
Lamination parameters

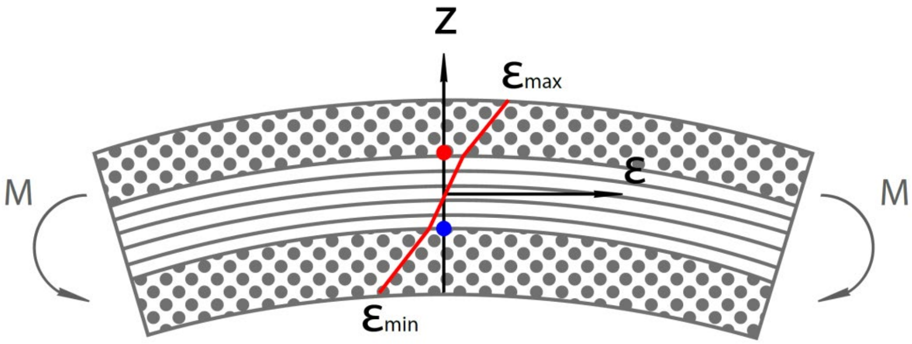
- Alternative higher level description of a laminate
- Lamination parameters have a feasible domain
- Reduction in design variables



Lamination parameters

- Sectional description cannot predict stresses
- Tsai-Wu failure criterion in sectional strain description
- Strength prediction is possible but conservative





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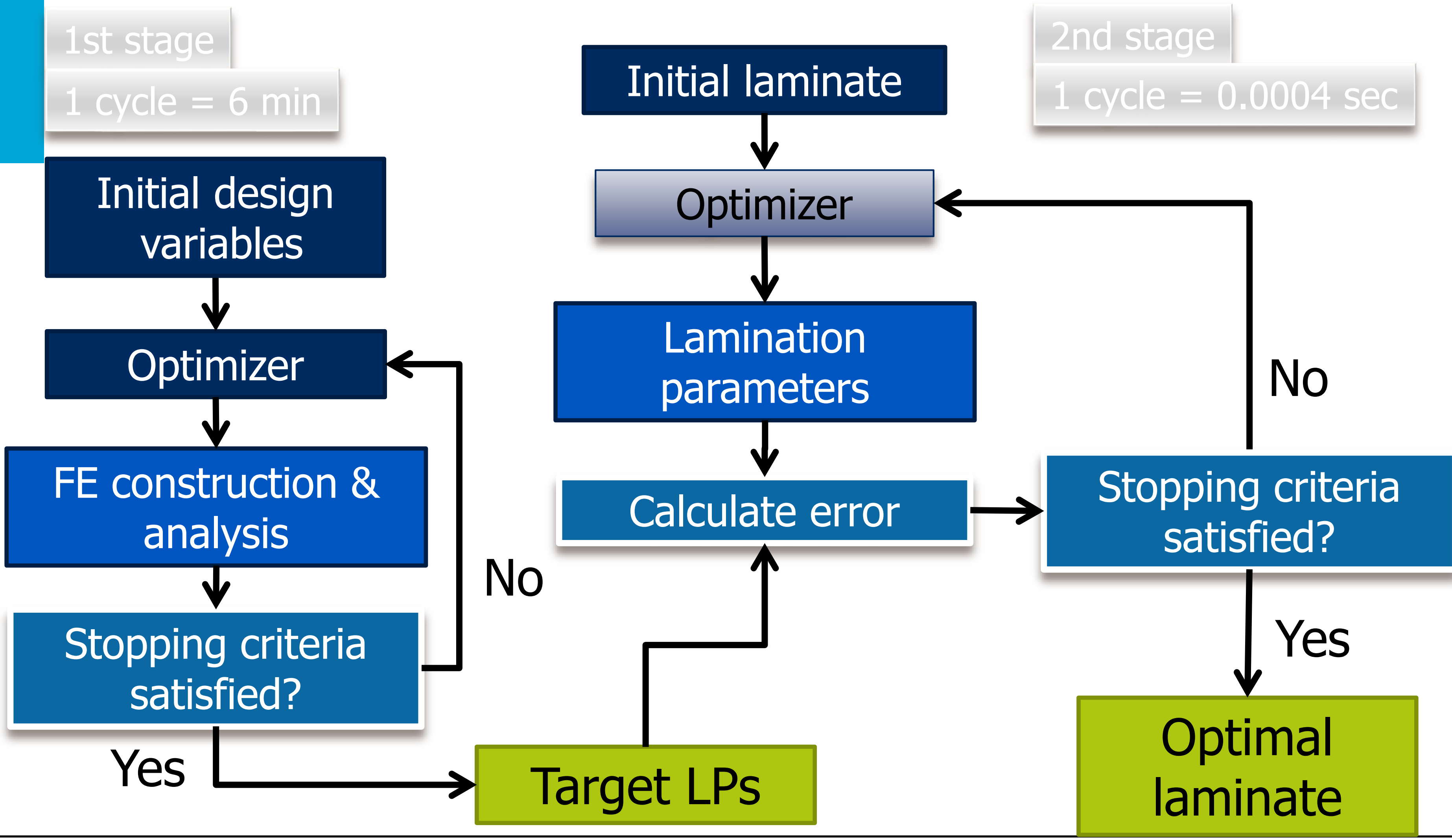
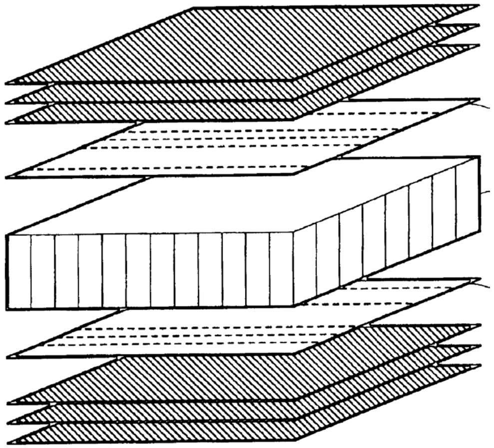
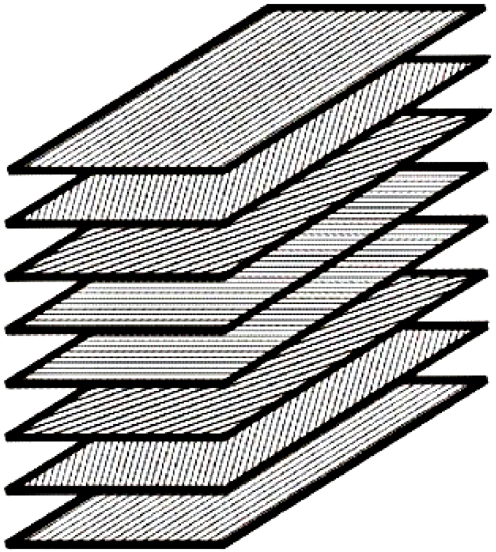
Two-stage weight optimization



Weight optimization (cont.)

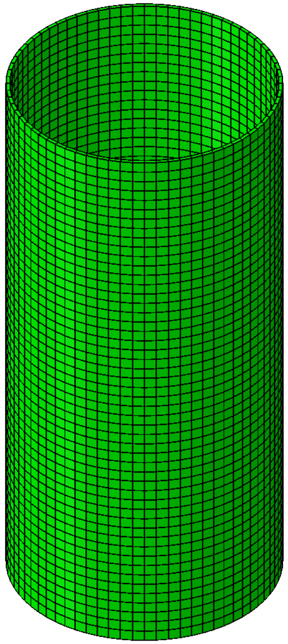
- Weight minimization of composite and composite sandwich FE pressure hulls
- Design variables are:
  - 5 for the composite (4 LPs and 1 thickness)
  - 7 for the sandwich (4 LPs and 3 thicknesses)





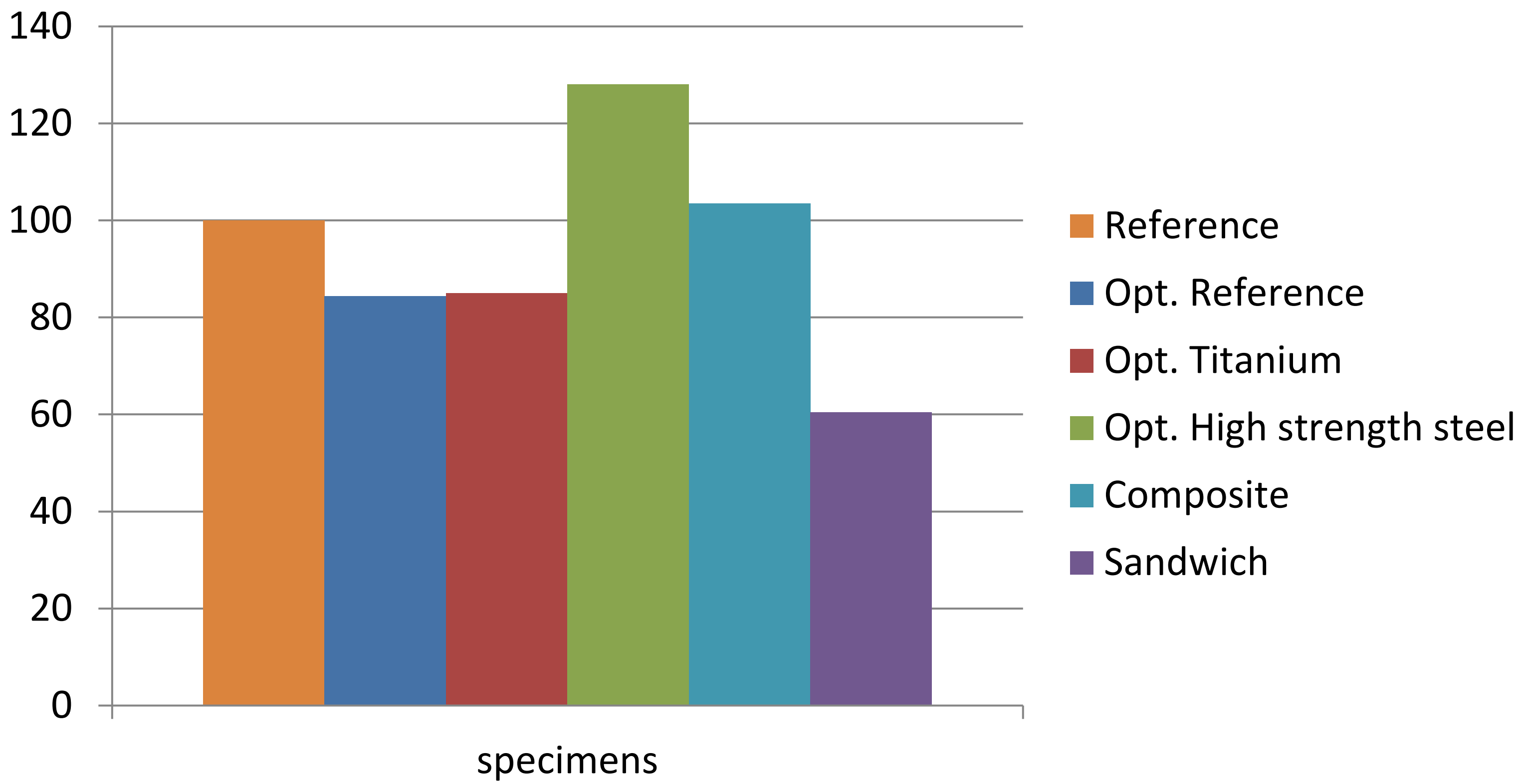
Weight optimization (cont.)

- Target lamination parameters are found in
  - 6 hours of calculation time for the composite
  - 20 hours for the sandwich
  - Remember the 39 weeks?
- Optimal laminates for 16 plies are found in seconds
- Calculation time is decreased with factor 325



Results

Weight compared to the reference model (100%)



Conlusions

- Is it possible to find a lightweight design framework that uses composite pressure hull FE models to accomplish an optimization procedure?

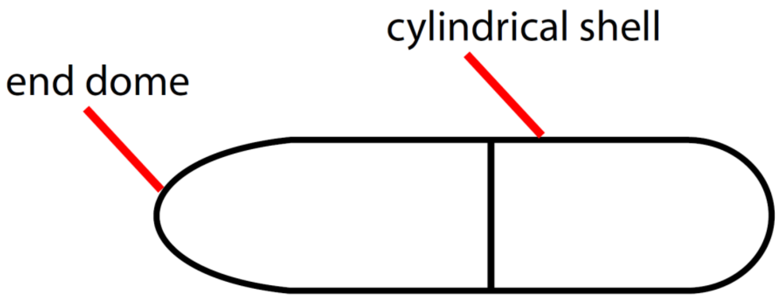
- Yes, the use of lamination parameters opens the possibility to formulate this framework!

Conclusions (cont.)

- For the considered external pressure, the sandwich design is shown to be at least 28% lighter than conventional designs
- Compared to the conventional steel pressure hull, a reduction of 50% in weight is possible, i.e. 15% of the total dry weight
- With this framework it is shown that composites are promising for lightweight pressure hull design

Recommendations

- Experimental validation has to be performed
- Scale effects have to be investigated
- The performance in terms of other operational requirements as e.g. other load cases has to be checked
- Complications that occur in full pressure hull design need to be investigated



Thank you for your attention!

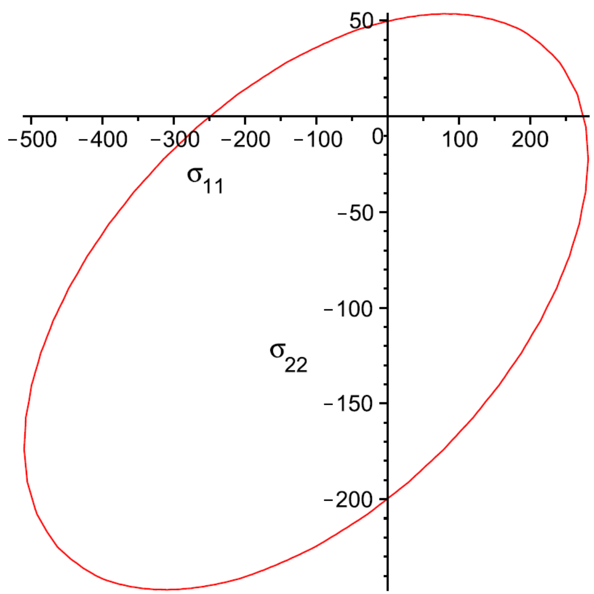
Appendix: Tsai-Wu sect. fail. fun.

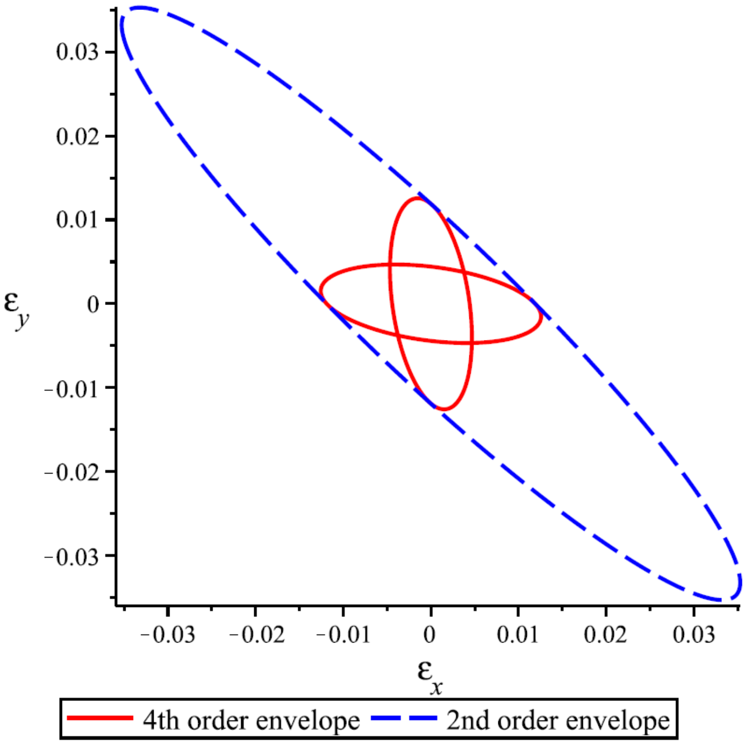
$$4u_6^2 I_2^2 - 4u_6 u_1 I_2^2 + 4\left(1 - u_2 I_1 - u_3 I_1^2\right)(u_1 - u_6) + (u_4 + u_5 I_1)^2 = 0\,,$$

$$u_1^2 I_2^4 - I_2^2 (u_4 + u_5 I_1)^2 - 2u_1 I_2^2 \left(1 - u_2 I_1 - u_3 I_1^2\right) + \left(1 - u_2 I_1 - u_3 I_1^2\right)^2 = 0\,,$$

$$\boldsymbol{\varepsilon}(x, y, z) = \boldsymbol{\varepsilon}^0(x, y) + z\boldsymbol{\kappa}(x, y)$$

$$z = \pm h/2$$





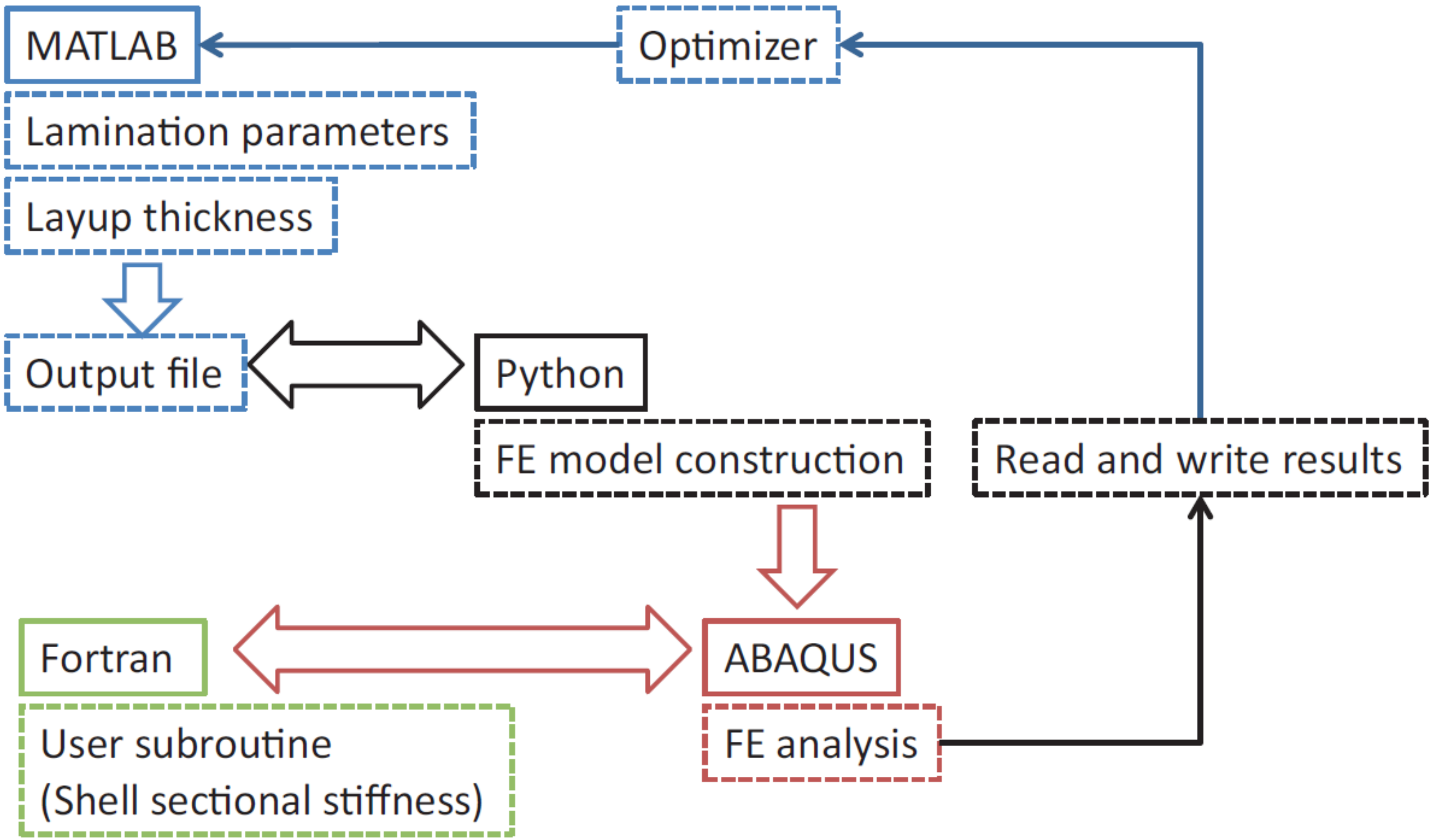
Appendix: Lamination paramters

$$\left\{ \begin{array}{c} \mathbf{N} \\ \mathbf{M} \end{array} \right\} = \left[\begin{array}{cc} \mathbf{A} & \mathbf{B} \\ \mathbf{B} & \mathbf{D} \end{array} \right] \left\{ \begin{array}{c} \boldsymbol{\varepsilon}^0 \\ \boldsymbol{\kappa} \end{array} \right\}$$

$$\left\{ \begin{array}{c} A_{11} \\ A_{22} \\ A_{12} \\ A_{66} \\ A_{16} \\ A_{26} \end{array} \right\} = h \left[\begin{array}{ccccc} 1 & \xi_1 & \xi_2 & 0 & 0 \\ 1 & -\xi_1 & \xi_2 & 0 & 0 \\ 0 & 0 & -\xi_2 & 1 & 0 \\ 0 & 0 & -\xi_2 & 0 & 1 \\ 0 & \xi_3/2 & \xi_4 & 0 & 0 \\ 0 & \xi_3/2 & -\xi_4 & 0 & 0 \end{array} \right] \left\{ \begin{array}{c} U_1 \\ U_2 \\ U_3 \\ U_4 \\ U_5 \end{array} \right\}$$

$$\xi_{[1,2,3,4]} = \frac{1}{2} \int_{-1}^{1} [cos(2\theta(\bar{z})), cos(4\theta(\bar{z})), sin(2\theta(\bar{z})), sin(4\theta(\bar{z}))] \, \mathrm{d}\bar{z},$$

Appendix: Optimization overview



Appendix: sandwich optimization